PLASMA SYSTEM AND METHOD FOR ANISOTROPICALLY ETCHING STRUCTURES INTO A SUBSTRATE

The present invention relates to a plasma system and a method for anisotropically etching structures, in particular structures defined using an etching mask, into a silicon substrate, using a plasma, according to the definition of the species in the independent claims.

Background Information

A method for high-rate plasma etching of silicon is known from DE 42 41 045 C1, etching being alternated with deposition of a Teflon-like polymer on the side walls of etched structures, which protects these walls from an etching operation during the following etching steps. Gases which provide fluorine radicals in plasma, such as SF_6, NF_3, or ClF_3, are used as the etching gases. Gases which provide Teflon-forming monomers in plasma, such as C_4F_8 or C_3F_6, are used as the passivation gases. This method allows etching rates of up to 20 µm/minute with excellent structure precision and selectivity even in regard to simple mask materials such as photoresist or SiO_2.

In the method according to DE 42 41 045 C1, comparatively short deposition steps and/or passivation gas steps and longer lasting etching steps are used in order to achieve the highest possible etching rate. Formulas in which passivation gas steps of 3 to 5 seconds each and etching steps of 10 to 12 seconds each alternate with one another are typically used in connection with inductively coupled plasma sources. In the case of shorter passivation gas steps, it becomes increasingly more difficult to reproduce them with the required precision over a very large number of cycles.

The object of the present invention is to provide a plasma system and a method which make(s) it possible to achieve a

higher etching rate when anisotropically etching silicon as the substrate in particular than in the related art, while simultaneously having greater profile control and also greater mask selectivity in particular.

Advantages of the Invention

In contrast to the related art, the method and the plasma system according to the present invention have the advantage of a higher etching rate, above all when anisotropically etching silicon as a substrate in particular, while simultaneously having greater profile control and additionally greater mask selectivity in particular.

It is advantageous in particular that the achievable etching rate and the structure precision increasingly improve with shorter cycle times of the passivation gas cycles, so that the very short passivation gas cycles used according to the present invention approach an "optimum" process in which no interruptions by passivation gas use and/or no passivation steps are necessary at all, but rather etching is performed uninterruptedly. However, such an "optimum" process would lead to undesired isotropic etching instead of anisotropic etching, while the process according to the present invention, in spite of the short passivation gas cycles, still allows anisotropic etching of structures.

The plasma system and the method according to the present invention thus allow extensive approximation of an "optimum process" while maintaining the anisotropy of the etching and high profile control and mask selectivity.

Furthermore, the plasma system according to the present invention has the advantage that it may be built on a typical plasma system having an inductively coupled plasma source, for

example, so that no significant system investments are necessary and/or existing plasma systems may be appropriately retrofitted without additional expenditure.

Advantageous refinements of the present invention result from the measures recited in the subclaims.

It is thus particularly advantageous that the method according to the present invention may be readily implemented through modification of the method for anisotropic etching of silicon according to DE 42 41 045 C1 or may be integrated therein, nearly uninterrupted plasma etching, which is distinguished by particularly high etching rates with particularly good structure precision and minimal undercuts or wall roughness, also being achievable in this case.

Furthermore, it is advantageous if, in the method on the basis of the method according to DE 42 41 045 C1, a passivation gas which provides the strongest possible passivation and Teflon-forming monomers is used as the passivation gas. In addition to C_4F_8 or C_3F_6, above all hydrofluorocarbons having an even lower fluorine to carbon ratio, such as C_4F_6 (hexafluoro-1,3-butadiene) or C_5F_8 (octafluoro-1,3-pentadiene) and, less preferably, even $C_2H_2F_2$ (difluoroethylene), are suitable for this purpose. C_4F_6, which forms polymers particularly efficiently, is particularly advantageous. These gases may preferably be removed from the buffer tank during the passivation steps with gas flow and/or material quantity which is reduced in relation to C_4F_8 or C_3F_6.

With the passivation gases C_4F_6 or C_5F_8, in addition to the gases C_4F_8 or C_3F_6, which are also usable, a more rapid polymer deposition from the plasma advantageously occurs overall with otherwise comparable plasma characteristic data, the deposited polymer additionally being denser and, thanks to the lower

fluorine to carbon ratio of these gases, also significantly more strongly cross-linked. In addition, it is more resistant to etching erosion because of a higher carbon content.

Since, when anisotropically etching silicon as in DE 42 41 045 C1, for example, in addition to the fluorine radical concentration available in the etching step, the efficiency of the buildup of a side wall polymer film as a protective film and its resistance in the following etching step play a decisive role in the process performance, significant improvement potential results directly therefrom.

In particular, the improved properties of the polymer deposited as a side wall film in the passivation steps in regard to density, cross-linking, higher carbon content, and increased resistance to etching erosion allow, in a process according to DE 42 41 045 C1, significantly shorter passivation gas cycle times of well below 1 second, for example, 100 ms to 500 ms, and also comparatively significantly lengthened etching gas cycle times from approximately 1 second up to 20 seconds to 30 seconds, i.e., the ratio of etching time to passivation time shifts significantly in favor of the etching time to values of 10:1 to 30:1 or even more. The higher chronological weight of the etching steps in the total process time leads directly to correspondingly higher etching rates.

A further mechanism in the direction of higher etching rates results from the described high carbon content of the side wall polymer films, their stronger cross-linking, and therefore their greater resistance to erosion.

Since, because of the very short passivation gas cycle times and the preferably used passivation gases C_4F_6 or C_5F_8 or even $C_2H_2F_2$, less side wall polymer material overall, in comparison

with the passivation gases C_4F_8 or C_3F_6, is initially eroded during the etching steps, which are isotropic per se, driven forward, and redeposited in lower-lying regions of the produced structures and/or the side walls of the produced trenches, which were just opened by the etching step, but because of the higher resistance of the produced Teflon-like side wall polymer films, a sufficient local passivation effect and local anisotropy of the etching step connected therewith are still achieved, so that less fluorine is lost through interaction with polymer materials and/or passivation gas components transported by ions during the etching steps. The achieved stronger C-C cross-linking also helps in this case, since fluorine radicals attack internal C-C bonds less than free external C bonds. This also increases the efficiency of the overall etching process.

The dynamics of the side wall polymer are known to have a large influence on the net quantity of available free fluorine radicals. A higher fluorine radical concentration, which is active in relation to silicon, together with greater permissible etching cycle durations and/or etching gas cycle times in relation to the passivation cycle durations and/or the passivation gas cycle times thus significantly increase the achievable etching rates.

Finally, the mask selectivity is advantageously improved in that the passivation coatings deposited on the mask used are also more resistant than in the related art due to the mechanisms described, and therefore the substrate masking, i.e., preferably the masking of a silicon wafer, is passivated particularly effectively during the etching process, in the case of a photoresist mask in particular.

Drawings

The present invention will be explained in greater detail on the basis of the drawing and in the following description. Figure 1 shows a schematic diagram of a plasma system within the scope of a first exemplary embodiment, and Figure 2 shows a detail from Figure 1 having a modified gas supply controller within the scope of a second exemplary embodiment.

Description of the Exemplary Embodiments

Figure 1 shows a plasma system 5 having an etching chamber 12 and a plasma source 19, as is largely known from DE 100 51 831 A1. In particular, an ion discriminator is located below plasma source 19 and has two coils which have a current flowing through them in opposite directions during operation, an upper coil 14 and a lower coil 13, and a drift zone, which is provided by a "spacer" or a spacer ring, for propagation of a plasma 22, produced in etching chamber 12 in the region of plasma source 19, in the direction of a substrate 21, such as a silicon wafer, which is preferably located on a substrate electrode 20. Furthermore, substrate electrode 20 is connected via a first impedance matching device 11 (first "matchbox") to a substrate bias generator 10. Plasma source 19 is preferably an inductively coupled plasma source having a coil 18, which is connected via a second impedance matching device (second "matchbox") to a coil generator 15. Finally, the etching chamber has a high-performance pump device 31 (merely indicated in Figure 1), via which etching chamber 12 may be evacuated. Reference is made to DE 100 51 831 A1 in regard to further details of the construction and operation of plasma system 5.

In contrast to the plasma system according to DE 100 51 831 A1, plasma system 5 according to the present invention has a modified gas supply device 32 of etching chamber 12. A feed line 23 is provided for this purpose, which is as short as

possible, preferably not longer than 20 cm, discharges into etching chamber 12, and is connected to an etching gas line 26 and a separate, independent passivation gas line 25. Furthermore, an etching gas valve 27 is provided upstream from the discharge of etching gas line 26 into feed line 23 and a passivation gas valve 28 is provided upstream from the discharge of passivation gas line 25 into feed line 23. Finally, a buffer tank 24 is inserted into passivation gas line 25 upstream from passivation gas valve 28. In addition, a buffer tank (not shown in Figure 1), which buffers the etching gas supply during the passivation gas cycles, i.e., when etching gas valve 27 is closed, may be provided in etching gas line 26 upstream from etching gas valve 27.

Valves 27, 28 are preferably positioned as close as possible to etching chamber 12, i.e., the gas lines which follow subsequent valves 27, 28 are as short as possible. Furthermore, buffer tank 24 is also to be positioned directly upstream from passivation gas valve 28. In addition, feed line 23 may be dispensed with completely if etching gas line 26 and passivation gas line 25 discharge directly into etching chamber 12 via two assigned inlet openings. In this case, valves 27, 28 are preferably each located directly upstream from these inlet openings on etching chamber 12.

Finally, a preferably programmable control unit 17, via which valves 27, 28 may be actuated, is provided in Figure 1. In addition, two mass flow regulators (not shown in Figure 1) are provided, which are positioned upstream from valves 27 and 28, respectively, and are assigned to etching gas line 26 and passivation gas line 25, respectively, or are integrated therein. Control unit 17 is preferably also connected to these mass flow regulators, as is explained in Figure 2 in the scope of a second exemplary embodiment. In this case, etching gas line 26 is assigned a first mass flow regulator 29 and

passivation gas line 27 is assigned a second mass flow regulator 30, which are preferably again positioned as close as possible to etching chamber 12. Alternatively, it is also possible to place mass flow regulators 29, 30 distal from etching chamber 12, in a "gas box," for example.

Control unit 17 is preferably integrated into the process sequence controller of plasma system 5 as a hardware component or represents a part of the process sequence controller, i.e., the software code in particular.

Buffer tank 24 preferably has a volume from 0.1 L to 1 L, for example, 0.5 L, and is particularly preferably made of stainless steel having electropolished internal walls. If a buffer tank is also provided in etching gas line 26 upstream from etching gas valve 27, it preferably also has an analogous design.

Etching gas valve 27 is designed as a "normally open" valve during operation of plasma system 5, while passivation gas valve 28 is designed as a "normally closed" valve. Valves 27, 28 discharge, as explained, as directly as possible into etching chamber 12, either separate short gas lines having the largest possible cross section and a length of at most 20 cm, or shared short feed line 23, also having the largest possible cross section, are provided for the outlets of etching gas valve 27 and passivation gas valve 28. The connection of buffer tank 24 to passivation gas valve 28 is also to have a length of less than 20 cm and is to be designed to have the largest possible cross section. In addition, it is possible and also usually advantageous to combine etching gas valve 27 and passivation gas valve 28 into a single changeover valve, which connects etching gas line 27 in the rest state and passivation gas line 25 in the activated state through to etching chamber 12. This results in perfect synchronization of

the opening and closing operations for lines 25, 27 in a simple way.

Using plasma system 5, structures which are exactly defined laterally with the aid of an etching mask are anisotropically etched in silicon, i.e., substrate 21, according to DE 41 42 045 C1, C_4F_6 preferably being used as the passivation gas. For this purpose, valves 27, 28 are alternately opened and closed. Passivation gas valve 28 and particularly also etching gas valve 29 are preferably rapidly switching valves, solenoid valves, for example, which may be activated directly using a 24 V signal, for example, and have switching times in the range of tens of milliseconds. If 24 V are applied in this case, etching gas valve 28 closes and shuts off the etching gas conducted in etching gas line 26 from etching chamber 12, while passivation gas valve 28 opens and releases the passivation gas conducted in passivation gas line 25 to etching chamber 12. Correspondingly, a changeover valve switches the etching chamber from etching gas to passivation gas, i.e., to buffer tank 24, when 24 V voltage is applied. Alternatively, pneumatic valves having electrical pilot valves are also conceivable for valves 27, 28, a slower response having to be accepted, however.

When plasma system 5 is operated in the scope of an etching method according to DE 42 41 045 C1, an etching gas flow of 300 to 1000 sccm SF_6, preferably 500 sccm SF_6, and a passivation gas flow of 10 to 500 sccm C_4F_6, preferably 50 sccm to 200 sccm C_4F_6 (sccm = cm^3/minute at normal pressure) are used. The power used at inductive plasma source 19 is from 2000 watts to 5500 watts.

Mass flow regulators 29, 30 assigned to etching gas line 26 and the passivation gas line, respectively, are each set to a fixed gas flow, for example, 500 sccm SF_6 and 100 sccm C_4F_6, in

a first method variation. The etching gas SF_6 first flows via open valve 27 into etching chamber 12, while the passivation gas C_4F_6 first fills buffer tank 24 and is prevented from flowing into etching chamber 12 by closed valve 28. After 5 seconds, for example, a short pulse is then sent to both valves 27, 28 by control unit 17, so that valve 27 closes and blocks the further flow of the etching gas into etching chamber 12 for a short period of time from 0.05 second to 1 second, preferably from 0.1 seconds to 0.5 seconds, while passivation gas valve 28 opens for this period of time and releases the pathway of the passivation gas into etching chamber 12, so that buffer tank 24 empties nearly instantaneously into etching chamber 12. After the preselected cycle time of 0.05 second to 1 second, for example, 0.3 second, has elapsed, valve 27 is opened again and valve 28 is accordingly closed again by appropriate electrical signals from control unit 17, i.e., the etching gas again flows into etching chamber 12 and the passivation gas again fills buffer tank 24 until the described switching cycle repeats after a further 5 seconds. 1 second to 15 seconds, preferably 2 seconds to 7 seconds, is set as the time interval between the passivation gas cycles, i.e., as the time duration of the etching gas cycles.

Overall, etching is performed the great majority of the time in this way and the etching procedure is only interrupted during the very short passivation gas cycles and a surge of passivation gas is fed to plasma source 19, so that a thin layer of Teflon passivation is laid over all etched structures and also provides the necessary side wall passivation for the following etching step.

In the method control described above, mass flow regulators 29, 30 operate continuously. The brief interruption of the access to etching chamber 12 is not significant in this case

for the etching gas flow and/or it may be captured as needed by the additional buffer tank described for the etching gas. The passivation gas flows continuously from second mass flow regulator 30 into buffer tank 24, which empties periodically into etching chamber 12 during the very short passivation gas cycles. The amount of passivation gas accumulated in buffer tank 24 before passivation gas valve 28 is opened thus determines the amount of side wall passivation which is incorporated in the etching process. For a time interval t_1 between the individual passivation gas cycles, which is synonymous with the time period of the etching cycles or the etching gas cycles in the described method control, the material quantity of the passivation gas accumulated in buffer tank 24 is equal to the product of gas flow and this time t_1. In an alternative second method control, second mass flow regulator 30 is additionally cycled in synchronization with the control of valves 27, 28 via control unit 17 according to Figure 2. This avoids the difficulty or disadvantage of the material quantity of the passivation gas which reaches etching chamber 12 during the passivation gas cycles being scaled directly with the time interval of the passivation gas cycles, which corresponds to the etching step duration, so that every change of the etching step duration or the etching gas cycle time also results in a change of the accumulated passivation gas quantity in buffer tank 24.

For example, if the time interval between the passivation gas cycles, i.e., the etching step duration, is halved, the time during which buffer tank 24 is filled with passivation gas is correspondingly also halved. In order to correct this halved charging time, the passivation gas flow to be provided by second mass flow regulator 30 must then be doubled in the process program via control unit 17.

This coupling of etching step duration or etching gas cycle time t_2 and time interval t_1 of the individual passivation gas cycles, which results in a comparatively complex process adaptation to the individual case, is preferably avoided in that second mass flow regulator 30 is switched to be active via control unit 17 only for a tank charging time t_L, which is shorter than etching step duration t_2. For this purpose, after the etching gas flow is reintroduced into etching chamber 12, second mass flow regulator 30 is switched off for a time span t_2-t_L, i.e., the requested passivation gas flow is set to 0 during this time. Second mass flow regulator 30 is again set to its setpoint gas flow until the end of the following passivation gas cycle and/or the beginning of the following etching gas cycle only after waiting time t_2-t_L has elapsed after the beginning of the etching step. In this case, for example, the values t_2=5 seconds, t_L=2 seconds, and the passivation gas flow 200 sccm are selected.

However, this method control also has the disadvantage that during the passivation gas cycles, not only the contents of buffer tank 24 flow into etching chamber 12, but a small amount of passivation gas is also subsequently supplied by second mass flow regulator 30 during the passivation gas cycle. Although the passivation gas cycle is short and this quantity is correspondingly small, the response behavior of passivation gas valve 28 is transferred into the process.

In third method variation, second mass flow regulator 30 is therefore controlled by control unit 17 so that the passivation gas flow is only regulated up to its setpoint value after passivation gas valve 28 is closed and remains there for tank charging time t_L, which is less than etching step duration t_2 or the time between passivation gas cycles t_1, but is regulated back down to 0 for remaining time t_2 or t_1 after t_L has passed. In this case, t_L is always less than t_1 or

t_2. The amount of passivation gas which flowed into buffer tank 24 during time span t_L thus remains trapped until passivation gas valve 28 is opened briefly and the stored passivation gas amount may flow over into etching chamber 12. During this time, second mass flow regulator 30 is still regulated to 0 and thus may not subsequently supply passivation gas. The supplied material quantity of passivation gas may be set particularly precisely with this method control and is determined independently of the switching behavior of passivation gas valve 28, which makes setting the process easier.

In a fourth method variation, on the basis of one of the described method variations, at least one of the parameters etching step duration t_2, tank charging time t_L, etching gas flow, passivation gas flow, or a substrate bias power coupled into substrate 20 via substrate electrode 20 is varied as a function of time so that the process first starts with a high proportion of passivation and the amount of deposited polymer is reduced continuously or in discrete steps during the process.

Although the described methods are independent of the details of a specific plasma source 19 per se, specific boundary conditions are to be taken into consideration. Thus, gas pulse operation, in which a significant material quantity of a gas suddenly flows into plasma source 19 to replace another gas, results therein in a sudden pressure increase and altered plasma conditions, also in regard to the gas types and their electronegativity.

In addition, for a method according to DE 42 41 045 C1, it is important for plasma 22 always to remain stable and well "matched" via second impedance matching device 16, i.e., for it not to go out or blink if possible. This requires a plasma

source 19 which is tolerant to process fluctuations. An inductively coupled plasma source 19 having a high coupled high-frequency power of 3000 watts to 5500 watts and an etching chamber having the smallest possible internal diameter of only 5 cm to 20 cm, in particular 9 cm to 15 cm, is thus preferably used in particular. The power per area in the region of plasma source 19 or at the location of substrate 21 is increased in this way by more than one order of magnitude to values of more than 5 watts/cm^2, in particular 20 watts/cm^2 to 30 watts/cm^2. A plasma 22 of this type is particularly tolerant to process parameter fluctuations.

In order not to impair the uniformity of the etching results over the surface of substrate 21 in this case in spite of diminished etching chamber 12, it is very advantageous to use the magnetic ion discriminator described in DE 100 51 831 A1 in combination with a drift zone in plasma system 5. This results in homogenization of the distribution of the neutral radicals from plasma 22 on their pathway from plasma source 19 toward substrate 21, while the magnetic ion discriminator ensures homogenization and/or focusing of the ion beam to substrate 21 and reflection of electrons. In addition, the magnetic fields generated via lower coil 13 and upper coil 14 also transfer to plasma source 19 itself and cause increased electron density in plasma 22 there, which is accordingly more robust and tolerant to sudden changes of essential gas parameters such as pressure, gas flow, gas type, and electronegativity.

As an alternative to the method variations described above, the use of valves which change over alternately between supplying etching gas and passivation gas to etching chamber 12 and a bypass line to a fore-vacuum pump (not shown in Figure 1) was also tested. This does allow the desired shorter cycle times, since then the regulating speed of mass flow

regulators 29, 30 is no longer decisive for the cycle times, but rather the closing times of the valves. However, this procedure has the disadvantage that a significant proportion of the costly process gases are lost unused and must be disposed of as exhaust gas. This is true in particular for the passivation gas, which must be supplied to etching chamber 12 only for the shortest possible time, but advantageously with a correspondingly large gas flow, and during the remaining time, i.e., the etching step duration and/or during the following etching gas cycle, flows out unused via the bypass line. This method is thus possible, but is comparatively costly.